

# **LIDAR REMOTE SENSING OF SOUND VELOCITY IN THE OCEAN**

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## **LONG-TERM GOALS**

My long term goals are the exploitation of physics for the solution of significant problems in oceanography. My interests generally lie in the direction of optics and laser interactions in the ocean.

## **OBJECTIVES**

Our goal is the rapid and accurate measurement of upper-ocean vertical sound velocity (and hence temperature) profiles in the ocean. The objective is to obtain range resolved ( $\approx 1$  m) measurements of temperature and sound velocity over a range of  $\approx 100$  m at an accuracy of  $0.1^\circ\text{C}$  and  $0.2$  m/s, respectively. To this end we are developing an innovative Brillouin LIDAR concept. Present results provide considerable confidence in the success of this objective.

## **APPROACH**

When a narrow linewidth laser beam propagates through water, it undergoes Brillouin scattering which produces two inelastically scattered Lorentzian lines centered symmetrically with respect to the transmitted laser line. In pure water, this scattering spectrum consists of essentially only this doublet. However, in the presence of hydrosols, an elastically scattered central line (also called the unshifted line, or improperly the Rayleigh line) appears. The so-called Brillouin shift, that is to say the frequency shift between the laser line and each of the Brillouin lines, is typically 7 to 8 GHz for water. The shift is proportional to both the refractive index and the sound velocity in the water; hence, it also has dependence on the salinity and temperature.

Our approach to sound speed (temperature) measurement involves measuring the Brillouin shift in a LIDAR return. The high spectral resolution required to determine the frequency shifts is achieved using the edges of absorption lines of  $\text{I}_2$  and  $\text{Br}_2$ . Simple normalization removes the dependence of the signal on variations in the amplitude of the lidar return. The concept is extraordinarily simple and robust.

Key individuals participating in the work are (1) Dr. Yves Emery: He received a one year post-doctoral fellowship from the Swiss National Science Foundation to work on this project. He has been a full-time participant and a major contributor to the successes. (2) Mr. Jeffrey Katz: He is a graduate student working full time on the project; this work will form his Ph.D. dissertation. (3) Dr. Thomas Walther: He is a post-doctoral fellow working part-time on the project. He has provided invaluable assistance in all aspects of the work. (4) Dr. Dahe Liu: He is a professor from Beijing University and just recently joined the project. He shepherded the acquisition from China of the iodine isotope  $\text{I}^{129}$  required for the frequency analysis of the LIDAR return.

## WORK COMPLETED

(1) We have used a pulsed laser to make measurements of the Brillouin spectrum produced by water.<sup>1</sup> These are the first pulsed laser measurements that show the Brillouin lines completely resolved in frequency.

(2) We have completed the first thorough analysis of the relations between Brillouin shift, index of refraction, sound velocity, temperature, and salinity.<sup>2</sup>

(3) We have completed rigorous calculations of a new ultra-high resolution spectrometer concept for the Brillouin shift discrimination. It is based on an excited state of Potassium in a Faraday Anomalous Dispersion Optical Filter (FADOF) and offers significantly greater flexibility than the  $I_2$  and  $Br_2$  absorption lines.

(4) We have designed and demonstrated a novel external cavity design that makes it possible to frequency double a cw diode laser (3 mW output at 1064 nm).<sup>3</sup> It employs a type II crystal, and does not require temperature stabilization. It is required for design of the Brillouin shift analyzer and for frequency stabilization of the diode laser that injection seeds the laser transmitter in the Brillouin lidar.

(5) In a related task, we have completed the analyses of our data on the optical absorption of pure water.<sup>4,5</sup>

## RESULTS

Technical results and their significance are discussed corresponding to each of the numbered tasks listed in the previous section, "WORK COMPLETED".

(1) We used a Fabry-Perot interferometer to obtain the first experimental frequency resolved measurements of the Brillouin lines with a pulsed laser. Fig. 1 shows a measurement of the frequency spectrum of the backscattered light at a water temperature of 29°C (corresponding to a Brillouin shift of 7.55 GHz). Data for only one free spectral range of the Fabry-Perot are shown in the figure. The solid line is raw data; no processing has been performed. The strong central

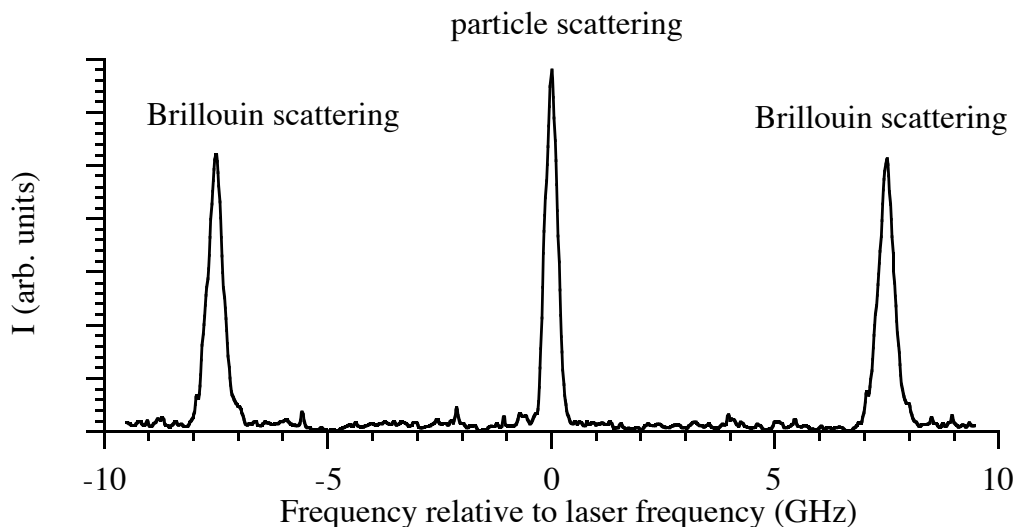


Fig 1. The first completely resolved experimental data for the Brillouin spectrum of water using a pulsed laser. Data were obtained at 29°C using the second harmonic of a pulsed injection seeded Nd:YAG laser (532 nm). The abscissa shows the frequency of the backscattered light relative to the laser frequency.

peak is due to particulate contamination in the water. Prior to our work, the available measurements using a pulsed laser did not demonstrate sufficient frequency resolution due to the pulsed laser linewidth and/or possibly poor collimation through the Fabry-Perot frequency analyzer.<sup>6</sup> The significance of this important result is twofold. First, it verifies that Brillouin shift data obtained with a pulsed laser can indeed be used to measure sound velocity and temperature in the ocean. Second, this system can now be used as a reference to study and analyze the Brillouin Lidar signals produced by our new detector concept (based on the edges of  $I_2$  and  $Br_2$  absorption lines).

(2) Several studies have discussed the potential accuracy of LIDAR measurements of sound velocity and temperature in the ocean from measurements of the spectral shift of the backscattered Brillouin lines. However, none has rigorously analyzed the interdependencies between the five relevant variables (Brillouin shift, sound velocity, refractive index, temperature, and salinity). We have completed such an analysis;<sup>2</sup> it is particularly significant since it is essential to determine realistic limits on the accuracy of temperature and sound velocity measurements via Brillouin scattering. We show that there are three relations among the five variables; thus, any two can be taken as independent, and the other three are then dependent variables. Since we measure the Brillouin shift, we take it as one of the independent variables. Since we found the dependence on salinity is relatively weak, and since relatively accurate values can be obtained from historical data, we take salinity as the other independent variable. The dependent variables (temperature, sound speed, and index of refraction) can then be evaluated using the measured Brillouin shifts and historical salinity data.

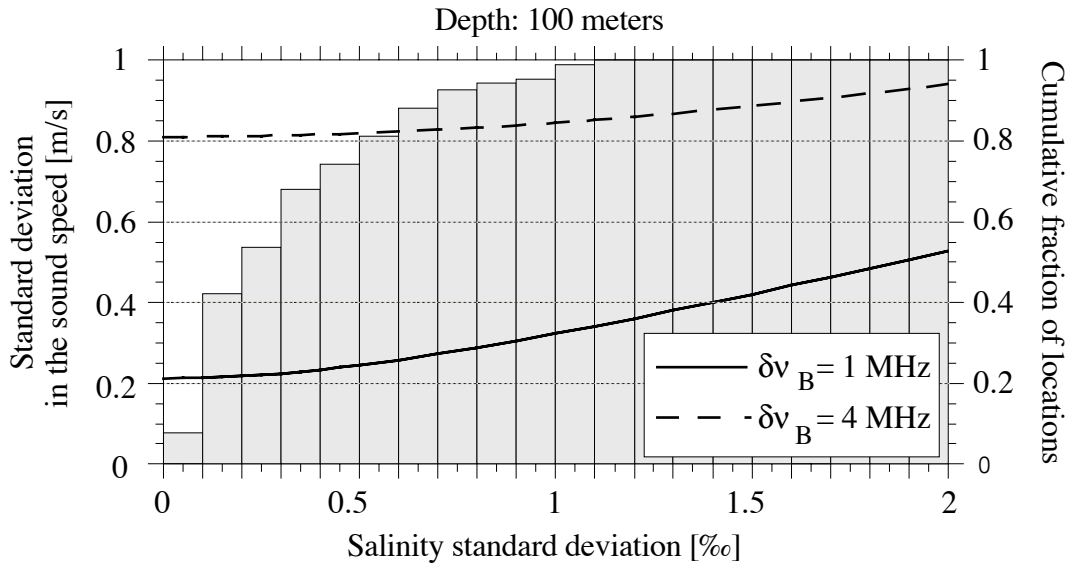


Fig 2. The uncertainty,  $\delta v_s$ , in the determination of sound speed (left axis) is plotted as a function of the standard deviation in the salinity, assuming an uncertainty in the measured Brillouin shift of  $\delta v_B = 1$  MHz (solid line) and  $\delta v_B = 4$  MHz (dashed line). In both cases we have assumed a Brillouin shift,  $v_B = 7.5$  GHz, and salinity,  $S = 35$  ‰. The background bar chart gives the cumulative fraction of locations (right axis) for which the standard deviation in historical data for the salinity is less than the value on the abscissa; this is based on more than 75,000 measurements at 113 locations.

For the salinity values we analyzed a very large set of *in-situ* oceanographic measurements,<sup>7</sup> and determined salinity mean values and standard deviations as a function of depth and location. The interesting feature in this compilation is the relatively small values of the standard deviations.<sup>2</sup> The uncertainty in the salinity limits the accuracy of temperature and sound velocity determinations

made via measurements of the Brillouin shift. The significance of this analysis is that our measurements of Brillouin shift combined with historical data for salinity can provide range resolved measurements of temperature and sound velocity down to 100 m depth with an accuracy of 0.1°C and 0.2 m/s, respectively. Results for sound velocity accuracy are summarized in Fig. 2.

Another significant aspect resulting from this analysis is the observation that one additional measurement or relationship would permit solution of the system for all five variables without use of historical data. We have investigated the possibility of a salinity-temperature relationship, but have only found a few locations where a relationship (weak) exists. Another possibility is a measurement of the Brillouin linewidth combined with a determination of its dependence on temperature and salinity; the FADOF described in (3) would make such a measurement possible.

(3) A new concept for a high resolution spectrometer to determine the Brillouin shift has been examined. The frequency discrimination with  $I_2$  and  $Br_2$  absorption cells is an edge filter<sup>8</sup> based on the sharp edges of their absorption lines; and, the frequency of the transmitted laser beam must be adjusted to a value providing absorption edges at the positions of the Brillouin lines. The new concept is still an edge filter, but this version uses a Faraday Anomalous Dispersion Optical Filter (FADOF) operating far out in the wings of an excited state transition in potassium.<sup>9,10</sup> It consists of a potassium atomic vapor cell located between two crossed polarizers, and subject to a homogeneous magnetic field along the optical path. The circular birefringence induced in the atomic vapor, in conjunction with the crossed polarizers, provides an optical filter with steep transmission edges, and high background rejection throughout the visible spectrum. The transmission edges can be adjusted to optimum values and the center frequency lies at the second harmonic of standard Nd:YAG lasers so that no major frequency adjustments will be required for the Nd:YAG laser. Our numerical simulations show that for a potassium FADOF with a cell of 1 cm length, a magnetic field of 1.4 kGauss, and a temperature of 310 °C, there will be transmission edges whose transmission will vary from  $\approx 0\%$  to nearly 100% within a 1 GHz band centered at  $\pm 7.5$  GHz from line center. An experimental demonstration of such a filter is underway. The results we have found for the FADOF are particularly significant because they will greatly simplify the Nd:YAG laser requirements, and because they may make it possible to also measure the Brillouin linewidth. The latter would offer the hope of eliminating the need for historical salinity data; in fact, the measurements themselves would provide salinity data.

(4) The frequency of the second harmonic (532 nm) of the pulsed Nd:YAG laser (1064 nm) used for the Brillouin lidar must be locked to the atomic or molecular transition used in the detection system. This is to be achieved by injection seeding the pulsed Nd:YAG laser with a cw 1064 nm diode laser whose second harmonic is locked to the appropriate atomic or molecular transition. The diode laser provides only 3 mW at 1064 nm; and, in order to frequency double such low cw power, we developed a new external ring cavity design. It uses an angle tuned KTP crystal with type-II phase matching, and does not require any temperature stabilization; the innovation is the use of an intra-cavity half-wave plate so that the cavity resonance condition is satisfied after two cavity round trips.<sup>3</sup> With 3 mW input at 1064 nm we obtain 15  $\mu$ W output at 532 nm; this is easily sufficient to appropriately lock the diode laser frequency. A patent disclosure has been made.<sup>11</sup>

(5) We have completed and published the analyses of our data on the absorption of pure water.<sup>4,5</sup> Although this is a side effort that is not essential to the Brillouin lidar effort, it is nevertheless very important and has had a major impact on ocean remote sensing.<sup>12</sup> Briefly, we find that the minimum in the absorption of pure water is at  $\approx 417$  nm and has a value  $0.0044\text{ m}^{-1}$ ; this is at a shorter wavelength and almost a factor of four lower, respectively, than has been previously generally believed.

## IMPACT/APPLICATIONS

The technology we are developing to remotely sense profiles of temperature and sound velocity in the ocean will provide the capability of rapidly monitoring the upper-ocean vertical structure for

much of the world's oceans and for most seasons. Such profiles will provide new perspectives on upper-ocean mixing and the oceanic internal wave field. Because of the high heat capacity and circulation in the oceans, temperature profiles are of critical importance to weather forecasting and to the understanding of ocean/atmosphere coupling and global change. Finally, sound velocity profiles are of direct strategic importance to the military mission since they provide support for both active and passive sonar functions; they would also provide an extensive new subsurface data source for operational nowcast/forecast systems.

## TRANSITIONS

The analyses of our data on the absorption of pure water have provided new, lower values for the absorption of pure water in its region of greatest transparency. These results have had a significant impact on models of the spectral reflectance of ocean water as a function of chlorophyll concentration and are seeing extensive use in these models. In fact, I understand our new results are now considered the standard accepted values for oceanographic purposes.

The new external cavity design for frequency doubling a very low power diode laser is a significant advance that could have widespread applications in consumer electronics - replacing red lasers with blue-green lasers.

## RELATED PROJECTS

This project was co-funded with a grant from the Texas Advanced Technology Program entitled "Depth Profiling of Temperature and Sound Velocity in the Ocean Using Brillouin Scattering".

In a direct spin-off from this project, we have developed a new concept for detection of submerged objects. It is a particularly significant advance in that even if an object is near or at the surface, it can still be detected with nearly 100% visibility; there are no problems with water surface reflections or bright daylight conditions. We are working with, and transferring this new concept to, a local small business, Lynntech, Inc. They submitted a Phase I SBIR proposal in July, 1997.

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